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Assessing industrial barriers of additively manufactured digital spare part implementation in the machine-building industry: a cross-organizational focus group interview study

Purpose:

Although additive manufacturing (AM) has been demonstrated to have significant potential in improving spare part delivery operations and has been adopted to a degree in the aviation and automotive industries, its use in spare part production is still limited in other fields due to a variety of implementation barriers. This purpose of this article is to assess the significance of previously reported barriers in the context of the machine-building industry.

Design/methodology/approach:

Adoption barriers are identified from literature and formulated as hypotheses, which are verified with a set of focus group interviews consisting of original equipment manufacturers, AM service providers, and quality inspection and insurance institutions. The results of the interviews are reported qualitatively, and the transcripts of the interviews are subjected to quantitative content analysis.

Findings:

The article identifies distrust in quality, insufficient material and design knowledge among stakeholders, and poor availability of design documentation on spare parts as the key barriers of adopting AM in the production of spare parts. The three key barriers are interconnected and training engineers to be proficient in design and material issues as well as producing high-quality design documentation will yield the highest increase in AM implementation in spare parts.

Originality/Value:

The article offers a unique approach as it investigates the subjective views of a cross-organizational group of industrial actors involved in the machine-building industry. The article contributes to the theory of digital spare parts by verifying and rejecting presented barriers of AM implementation and how they are interconnected.

Keywords: additive manufacturing; 3D printing; digital spare parts; implementation barriers; qualitative content analysis; focus group interview research

1 Introduction

Additive manufacturing (AM) was initially commercialized in the 1980s as a method to build prototypes from plastics. As the technology group matured, more materials became available and tooling applications became possible (Rayna and Striukova, 2016). As a result of further technological advances, the use of AM to produce end-use parts has become a subject of much industrial interest and has been described as disruptive for traditional supply chains (Steenhuis and Pretorius, 2016; Strong et al., 2020). The implication that AM can be used to produce end-use parts has caused interest in the production of spare parts from digital data instead of holding a steady physical inventory of spare parts. The term “digital spare part” (DSP) has been used to describe this concept (Chekurov et al., 2018).

In literature, AM is presented as a possible solution to prevalent challenges in spare part management. Based on an industrial survey investigating the importance of characteristics of spare parts, Roda et al. (2014) reported that high stock-out cost, long lead time, and low demand predictability are the critical characteristics. In reflection of these characteristics, AM can aid in avoiding stock-out costs by improving the lead time of spare parts (Meisel et al., 2016; Chiu and Lin, 2016; Oettmeier and Hofmann, 2016), and improve inventory performance and the response to unpredictable demand swings through less reliance on buffer stock (Ford and Despeisse, 2016; Muir and Haddud, 2018; Zhang et al., 2019). The drivers of AM behind these benefits are its ability to be cost-effective in low-volume production of parts in lot sizes of one and the absence of equipment changeover (Fontana et al., 2019; Khorram Niaki et al., 2019).

The body of literature surrounding additively manufactured spare parts has been rapidly growing ever since the concept was originally presented by Pérès and Noyes (2006). In recent literature, Ghadge et al. (2018) note that implementing AM in spare part production has a strong potential to mitigate high inventory risk and achieve a high service level while eliminating downtime cost. In the same vein, others have noted that benefits of AM in relation to spare parts are reduced stock levels and tooling costs (Bogers et al., 2016; Wagner and Walton, 2016 Knofius et al., 2019b), and improved ecological footprints (Rylands et al., 2016; Li et al., 2017). Moreover, the required digital files and raw materials easily bypass physical borders, allowing AM to improve product availability in hard-to-reach locations (De la Torre et al., 2016; Holmström et al., 2017). Furthermore, consolidating multiple spare parts into one part has also been investigated and shown to provide some benefit in total maintenance costs (Knofius et al., 2019a). AM also allows for the introduction of upgrades through refurbishment during the life cycle of the product (Bournias-Varotsis et al., 2019; Coro et al., 2019).

The match between spare parts and AM is therefore clear and additively manufactured spare parts are already in use in some leading sectors, such as automotive and aviation, which has been reported in academic publications (Delic et al., 2019; Khajavi et al., 2018; Togwe et al., 2019) and prominent corporate press releases (Daimler AG, 2018; Satair, 2020; Volvo, 2018). However, although AM offers many advantages, and the benefits are clearly presented in literature, the use of AM in spare part production is still very limited in sectors outside of the spearhead due to a variety of barriers (Thomas-Seale et al., 2018).

This article is motivated by gaps in the scientific discourse regarding explanations for the lacking presence of additive manufacturing in spare part production in sectors other than automotive and aviation. The article takes the machine-building industry as an example of an industry with much potential in implementing additive manufacturing in spare part supply operations, but which so far has not implemented them to a meaningful degree. The machine-building industry produces and maintains machines for consumers and other companies. Specifically, the industry sector addressed in this article manufactures and maintains general-purpose machinery and equipment, typical examples of which are lifting equipment, furnaces, and machine tools. The machinery and equipment require regular or emergency maintenance, which causes a great reliance on good spare part practices and a focus on spare parts in general. The components constituting the product offerings of the machine-building industry use the full spectrum of materials from plastics to metals and part sizes from a few cubic millimeters to several cubic meters for individual components. The study presented in this article was conducted to identify the severity of the barriers that are delaying the wide adoption of additively manufactured spare parts in the machine-building industry, with the goal of identifying the critical barriers.

The structure of the article is as follows. First, adoption barriers previously identified for AM in literature regarding spare part production and supply chain integration in general are extracted and taken as hypotheses. The development and execution of the focus group interviews conducted to verify or reject the hypotheses is then described. Then, the methods of qualitative and quantitative analysis of the data acquired from the focus group interviews are described. In the quantitative approach, the transcripts of the interviews are coded, the internal reliability of the method verified, co-occurrence analysis conducted, and the frequency and co-occurrence of codes reported. The role of the qualitative analysis in this study is to provide context and depth to the quantitative analysis through interpretation of the interviewee comments and in-vivo quotations. Finally, the results of the qualitative and quantitative methods are combined in the discussion section to examine the validity of the barrier hypotheses and recommendations are given on how to approach overcoming the barriers.

The existing literature on additively manufactured digital spare parts is heavily biased towards the theoretical benefits of the concept and fails to elucidate why the concept is not broadly used. Moreover, the few explanations given in the literature conflict with each other. The article contributes to the theory of digital spare parts by providing an explanation for the lower-than-expected adoption of the concept and clarifies the conflicting barriers presented in literature. The key practical contribution of the article is that it gives researchers, educators, and industrial managers an indication of which barriers should be addressed for highest impact. A significant aspect of originality of the article is the fact that the focus groups interviews are conducted with representatives from original equipment manufacturers (OEMs), AM service providers, and insurance and quality assurance institutions. This is the first time, to the knowledge of the authors, that such a cross-organizational focus group interview study has been conducted on the barriers of additively manufactured spare part adoption.

2 Adoption barriers in literature and hypothesis development

While there are many articles that investigate the benefits of AM in spare part production, there are far fewer articles critically addressing the delayed implementation of the concept. A small number of papers have specifically addressed the barriers of AM in spare part production. Kretzschmar et al. (2018) conducted a survey mainly on technical barriers, Ballardini et al. (2018) examined mostly intellectual property rights (IPR) issues, and Heinen and Hoberg (2019) conducted a battery of interviews on a holistic level. Other articles combining AM and spare parts, while not focusing on barriers, briefly hypothesize on them in their discussion sections (Chekurov and Salmi, 2017; Chekurov et al., 2018; Frandsen et al., 2020).

Due to the scarcity of literature that explicitly addresses barriers of additive manufacturing implementation in spare part supply, literature combining supply chains and AM without a specific focus on spare parts is used as an additional resource to build the barrier hypotheses. The two central works are an article by Martinsuo and Luomaranta (2018), who delineated a comprehensive list of technology-related, strategic, supply chain-related, operational, organizational, and external challenges in AM, and an article by Durach et al. (2017), who identified and ranked fifteen mostly technical barriers of adoption of AM in supply chains based on a multi-stage survey. The hypothesis grouping for this study follows the example of Martinsuo and Luomaranta (2018) but combines strategic and supply-chain related barriers as well as operational and organizational barriers. A variety of articles not focusing on barriers of AM implementation, but that nevertheless address them in their discussion sections, are used to augment the literature (Holmström et al., 2016; Holmström et al., 2017, Weller et al., 2015; Ryan et al., 2017; Verboeket and Krikke, 2019; Steenhuis and Pretorius, 2017; Thiesse et al., 2015; Rogers et al., 2016; Dwivedi et al., 2017; Yi et al., 2019; Murmura and Bravi, 2018; Wagner and Walton 2016).

2.1 Technical barriers of additive manufacturing in spare part production

Holmström et al. (2017) reported that AM was insufficiently mature to replace conventional manufacturing in spare part production due to quality issues. Chekurov and Salmi (2017) presented that the surface quality is insufficient for cosmetic spare parts and post-processing is often required to make them acceptable, which affects the viability of using AM in spare part production. The insufficient accuracy of AM has also been reported as an insurmountable issue for additively manufacturing spare parts (Kretzschmar et al., 2018). The implementation of AM in spare parts is further hampered by the varying quality between batches created with similar AM machines (Chekurov et al., 2018), and a limited range of raw materials (Kretzschmar et al., 2018). Finally, quality control structures are reported to be inadequate because of the differences between traditional manufacturing and AM (Weller et al., 2015). Similarly, Bonnín Roca et al. (2019) mentioned that achieving control of AM process on a sufficient level to meet standards is one of the main barriers of AM adoption.

According to Kretzschmar et al. (2018), the slow speed of AM is a major hinderance of its adoption in spare parts. Ryan et al. (2017) mentioned that there are major barriers related to the trustworthiness and steadiness of the AM manufacturing production process, confined dimensions of the manufacturing chamber, and high cost of machinery. Martinsuo and Luomaranta (2018) mentioned material and quality challenges, long production time, size limitation, technological immaturity, and missing cost calculation models as technical challenges. In Durach et al. (2017), the three highest-rated barriers were explicitly related to material and quality: limited variety of materials, difficulties regarding the development of new materials, and insufficient quality of parts. Reliability, speed and size limitations were likewise ranked high: #4, #6, and #7 respectively. On the other hand, high manufacturing and equipment costs were ranked as minor barriers at #13 and #14.

This is used to formulate the first two hypotheses:

H1: *The quality of additively manufactured spare parts is currently insufficient or is insufficiently controlled to replace conventionally manufactured spare parts.*

H2: *The cost-effectiveness, throughput and maximum part size of AM are currently inadequate to replace conventionally manufactured spare parts.*

2.2 Structural barriers of additive manufacturing in spare part production

The legal, copyright-related and IPR issues were brought to attention in detail by Ballardini et al. (2018) who claim that these issues form a major barrier for AM implementation in spare parts. According to Steenhuis and Pretorius (2017) and Verboeket and Krikke (2019), rules, laws and regulations regarding AM are lacking for wider implementation of AM in spare parts. Similarly, Thiesse et al. (2015) mentioned unclearness about accountability, warranty policies, quality assurance, inspection and testing standards as barriers of AM. Holmström et al. (2016) and Wagner and Walton (2016) mentioned ambiguity regarding intellectual property rights as major barriers of implementing AM in spare parts.

Ballardini et al. (2018) presented that IPR issues must be overcome before AM can be used in spare parts. In order to achieve this, safe ICT structures are required to prevent knowledge leaks and piracy in the implementation of additively manufactured spare parts (Rogers et al., 2016). Chekurov et al. (2018) noted that the existing ICT structures may be insufficient for reliably and securely transferring the correct spare part data to the spare part manufacturer in global, decentralized operations. The supply chain-related barriers mentioned by Martinsuo and Luomaranta (2018) were the lack of digital solutions through which data travel safely between actors and the uncertainty of the future supply chain structure.

This is used to formulate the next two hypotheses:

H3: *Lacking regulatory structures prevent the implementation of additively manufactured spare parts.*

H4: *Existing ICT structures are insufficiently safe, secure, and robust to implement AM in spare parts.*

2.3 Operational barriers of additive manufacturing in spare part production

Several articles propose that traditional manufacturing knowledge may become redundant when AM is introduced in supply chains, while new positions may appear that require new knowledge about AM production, designing for AM (Thiesse et al., 2015) and AM cost calculation (Dwivedi et al., 2017). Although companies can be well-aware of the theoretical potential benefits of AM in spare part production, they find it difficult to identify the real-life opportunities of AM and also seem to frequently lack a concrete overview of how AM can benefit them, despite knowing individual theoretical benefits (Heinen and Hoberg, 2019). Lack of expertise and organizational transformation were also noted by Yi et al. (2019) as common barriers for AM implementation. Specifically, they listed the lack of methods for designing products, lack of material performance knowledge, and lack of AM software as the greatest issues. Murmura & Bravi (2018) also noted that more knowledge and training is often requested by companies, but that this need is not as strongly present with companies that have started using AM.

Dwivedi et al. (2017) expected resistance to change from workers due to lacking trust in AM and lacking governmental and managerial support. The operational and organizational barriers presented by Martinsuo and Luomaranta (2018) were difficulties in identification of right components for AM, the habit to sticking to old practices, and a general lack of knowledge and readiness.

This is used to formulate the last two hypotheses:

H5: *Lacking knowledge about AM prevents its implementation in spare parts.*

H6: *Resistance to change prevents the implementation of AM in spare parts.*

3 Methods

To evaluate the correctness of the hypotheses for the barriers causing the delayed widespread AM implementation in spare part production in the machine-building industry, subjective information is acquired from individuals who have an influence on the implementation of AM. To this end, focus group interview is chosen as a suitable method of data collection (Flick, 2014).

A focus group interview is a qualitative research method in which a group of people from specific backgrounds is invited to discuss specific topics aided by a moderator (Fontana and Frey, 2000). Focus group interviews are used especially in marketing and media research, but they can be used in any explorative studies to generate and verify hypotheses based on informants' insights (Morgan, 1988). The use of focus group interviews in engineering research has been limited, but it has been reported to lead to in-depth results unachievable with quantitative methods in certain conditions (Kontio et al., 2004). Focus group interviews are a suitable method to verify hypotheses whose answers lie in the perceptions and attitudes of industrial actors, which is especially seen as a strength of focus group interviews when compared to surveys (Sharma et al., 2017).

3.1 Focus group interview process

The presented literature and the study hypotheses were used to formulate the focus group interview questions as per Ulrich (1999). The focus group interviews were conducted according to a fixed list of background questions, direct questions, and indirect questions. The direct questions *4-6* were designed so that they would capture the area of interest as widely as possible. The direct questions for probing the hypotheses were designed by the authors based on the common themes of the three groups of hypotheses. The background questions *1-3* were used to warm up the interviewees, and the indirect questions *7-9* were designed to approach the subject indirectly without a direct link to hypotheses to capture data that would not be produced directly. The question design for background questions and indirect questions was based heavily on a similar study reported by Chekurov et al. (2018). The focus group interview questions are presented in Table 1.

Table 1. List of questions of the focus group interviews

(1) What benefits are you expecting from digital spare parts?
(2) How do you see the exploitation of digital spare parts in your company?
(3) What kind of parts would bring the biggest benefit?
(4) Is additive manufacturing good enough for your needs? Why not?
(5) Do you see risks related to digital spare parts?
(6) Why are digital spare parts not widely used?
(7) How can potential digital spare parts be recognized?
(8) Who could suggest the use of a digital spare part?
(9) What special requirements do spare parts have from your perspective?
(10) What will the workflow of digital spare parts be?
(11) How interesting are smart spare parts?

(12) How will your company benefit financially from digital spare parts?

All interviewees in each group were consecutively asked the questions listed in Table 1. Once all interviewees had had a chance to answer, specific points expressed by interviewees were returned to and the topics were discussed between the interviewees. To elicit responses from all participants equally and to avoid having specific people dominate the conversation, Post-it notes were used at the beginning of questions that were foreseen to be challenging to answer, as suggested by Peterson & Barron (2017). Dozens of Post-it notes were generated per question and they were collected and formed part of the qualitatively processed data.

Stage directions for interviewing as given by Herrmanns (2004) were used to ensure that all moderators acted and instructed similarly in the focus group interviews. An explanation was given to the interviewees regarding what was expected from them during the focus group interview, an informal atmosphere was created, and room was given to interviewees to freely present their experiences and opinions. The participation of the moderator was kept to the minimum to avoid disturbing the participants' own initiative. The focus group interviews were recorded for later transcription. The participants were interviewed for two hours using the predetermined questioning routine.

3.2 Moderator data

Ten researchers of AM acted as the facilitators of the focus group interviews. Each group had a main moderator and a secretary so that the main moderator could fully concentrate on managing the group, as suggested by Patton (2002). The role of the secretary was to create field notes to capture information that would not appear in the audio recording. The groups were run simultaneously, and they all lasted approximately two hours.

3.3 Interviewee data

The participants were invited via a project mailing list consisting of interested parties compiled during a project on the use of AM in spare parts. The mailing list contained individuals from AM service providers, OEMs interested in implementing additively manufactured digital spare parts, and quality inspection and insurance institutions. The participants were not compensated. Twenty-four participants were interviewed in the focus group interviews held in Espoo on 1.11.2018. The participants were asked to fill in a questionnaire regarding their background before the sessions, as suggested by Witzel and Reiter (2012). The anonymized and compiled information is provided in Table 2.

Table 2. Anonymized participant data.

Position in Company	
Top management	6
Middle management	5
First-line management	4
Specialist	9
Company type	
AM service provider	11
OEM	10
Quality inspection and insurance	3
Level of education	
Upper secondary education	4
Bachelor	9
Master	8
Doctor	3
Work experience in related fields	
Average	13.7 years
Median	15 years
Work experience in 3D printing	
Average	4.13 years
Median	3 years

The participants were divided into groups according to their company type and position in company. The division was made according to the following classification:

- Group 1: AM service providers, operational staff
- Group 2: OEMs, managerial staff
- Group 3: Quality inspection and insurance institutions
- Group 4: OEMs, design engineers
- Group 5: AM service providers, managerial staff

One of the goals in group formation was to avoid multiple people from the same company in the same group. Because some companies were represented by multiple participants, the criteria for group formation were not absolute and a few participants were placed in another group. This was considered in the analysis of the results so that the views of a certain group would not be represented by a person from another background.

3.4 Coding process

To ensure that the focus group interview data were reliable and could be interpreted objectively, the method required a systematic coding process performed by multiple coders. In the context of focus group interviews, coding is the act of going through the transcripts and identifying sections that are relevant to the hypotheses. These sectors are marked with labels, or codes, which can be words or short sentences (Stewart et al., 2007). The allocation of codes, their co-occurrence analysis and interrater reliability calculation were performed in Atlas.ti 8.

The coding procedure was set up according to the thematic coding and content analysis presented by Braun and Clarke (2006). The codes were generated during an initial pass of open coding of the transcripts by the lead coder, which means they emerged from data and were not imposed upon it a priori, as per Hood (2007). As the codes were developed inductively by one coder, their use must be verified by verifying coders. One lead coder and four verifying coders analysed the transcripts and assigned codes to the sections relevant to the hypotheses.

3.5 Interrater reliability

Once the coded transcripts were obtained, the code patterns of each researcher were compared with one another to calculate the reliability of the data by calculating the amount of overlap of identical codes given to the same blocks of text by separate coders (MacPhail et al., 2016). The statistical measure of Krippendorf's alpha coefficient is used. Krippendorf's alpha is calculated using Equation 1 (Krippendorff, 2018).

$$\alpha = 1 - \frac{D_o}{D_e} \qquad (1)$$

where D_o is the observed disagreement and D_e is the expected disagreement when coding is conducted by chance.

The inter-coder agreement function in Atlas.ti 8 was used to compute the Krippendorff's alpha across all codes, all interviewed groups, and all coders. The resulting coefficient was 0.727, which was above the data reliability threshold of exploratory research, 0.667.

3.6 Code co-occurrence analysis

The connections between codes were examined with code co-occurrence analysis to discover which codes appeared together most consistently, potentially indicating meaningful relationships between the codes. A co-occurrence matrix was generated with Atlas.ti 8 to obtain the co-occurrence coefficients for pairs of codes (Saldaña, 2013; Thairu and Johnson, 2007). To analyse the relationships of the codes, the co-occurrence coefficients between the twenty most commonly occurring codes and all codes that appeared more than ten times in the transcripts were obtained. Based on the highest co-occurrence coefficients, a network representation was created to represent clusters of codes and to visualize strengths of the connections between codes, as per Pokorny et al. (2018).

4 Results

4.1 Code frequency and co-occurrence

Figure 1 presents the ten most common codes attributed to the transcript of each group.

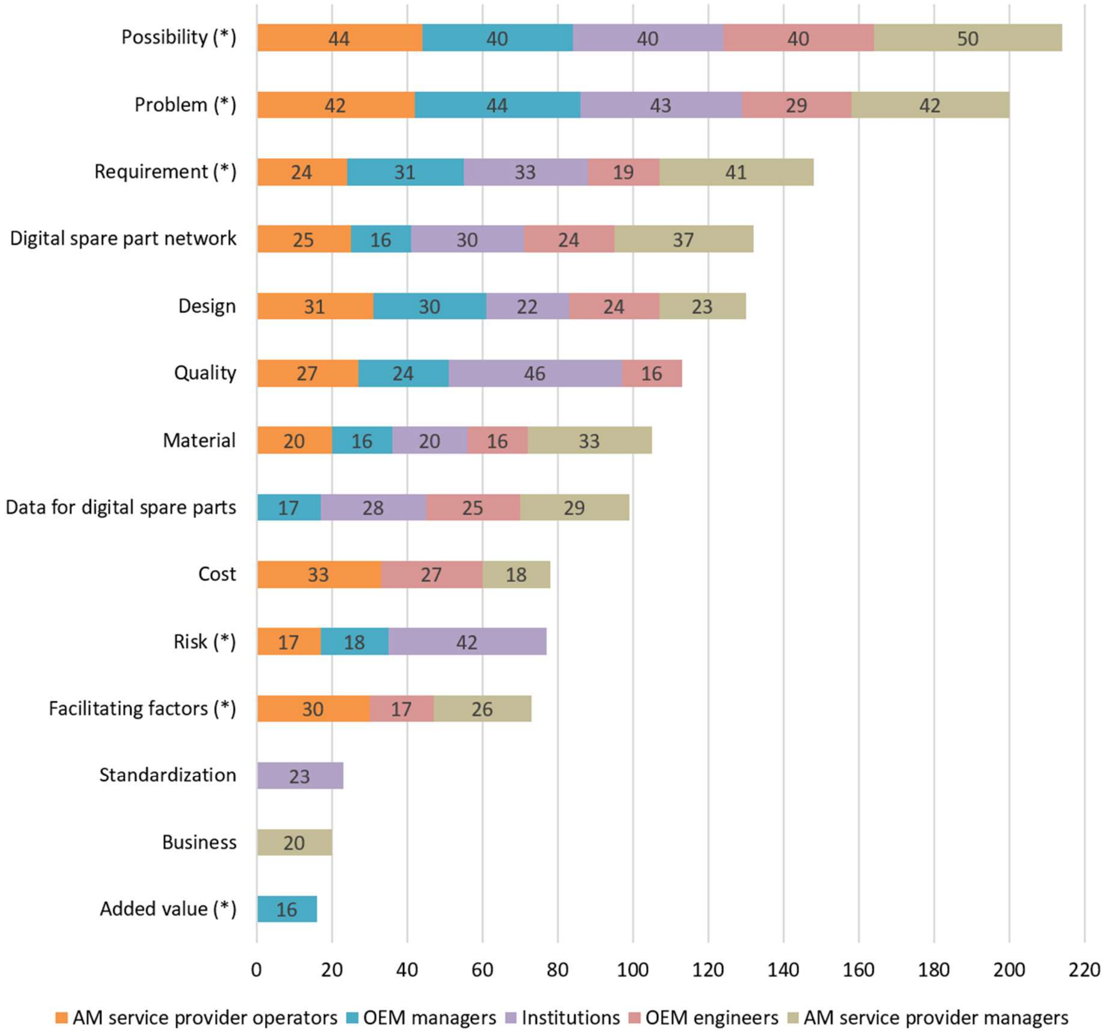

Figure 1. The ten most frequently occurring codes in each interviewed group. Modifier codes are marked with an asterisk.

In code frequency analysis, codes were counted equally regardless of their context, meaning that the frequent appearances of the code “design”, for example, did not indicate whether the interviewees considered it a barrier (Thairu and Johnson, 2007). To provide context and to give depth to the analysis, the coders also applied modifier codes, such as “possibility”, “problem”, and “requirement”, which only had significance when used in conjunction with another code. In contrast, codes such as “digital spare part network”, “design”, and “quality” had significance on their own. The modifier codes associated with barriers were "problem", "risk" and "requirement". The strongest relations of the codes are presented in Figure 2.

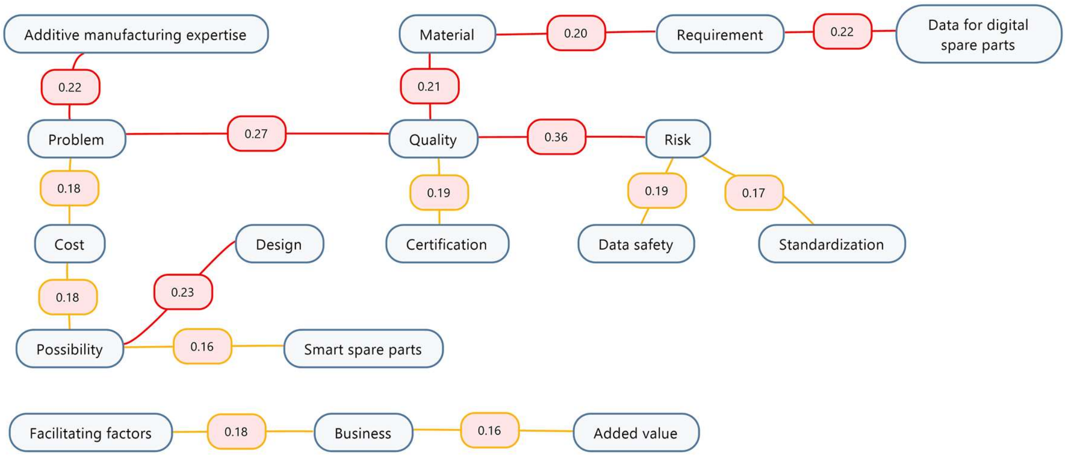

Figure 2. A co-occurrence network of codes that most appear in conjunction with others. Red connections are co-occurrences with a coefficient of over 0.2 and yellow lines are co-occurrences with a coefficient between 0.15 and 0.2.

While "digital spare part network" was a commonly appearing code, it was not consistently used in conjunction with other codes and does not appear in the co-occurrence network. Several clusters are formed around the modifier codes, as well as the code "quality", which is not a modifier code but is a central topic. An entirely separate cluster also formed around the code "business".

4.2 Qualitative focus group interview answers

The in-vivo quotations presented in this section are translated from Finnish while maintaining their original tone, except for group 5 whose in-vivo quotations are reproduced verbatim because it was conducted in English. The qualitatively analysed answers to the focus group interview questions organized by groups are presented in Table 3.

Table 3. Qualitatively analysed answers acquired from the focus group interviews

Question content	*AM Operators*	*OEM Managers*	*Quality inspection and insurance*	*OEM Designers*	*AM Managers*
Benefits of additively manufactured digital spare parts	• Simplified spare part delivery • Improved availability of spare parts • Positive environmental impact • Updated parts • End users creating spare parts • Reduced warehousing	• Improved products • Faster delivery • Customized parts	• Faster delivery • Manufacturing on demand • Flexible availability • Positive environmental impact • Updated parts	• Faster delivery • Improved availability of spare parts • Reduced warehousing • Easier predictive maintenance	• Increased uptime • Updated parts • Savings from no tooling
Use of digital spare parts in the company	• Manufacturing spare parts for companies	• Digital spare parts improve customer service level	• Not applicable	• Used in extreme rush cases	• Providing digital spare parts as a service to companies
Parts with biggest benefit	• Parts that are no longer available • Critical but do not endanger human lives • Parts with high inventory costs • Parts that are frequently updated • High production volumes	• Parts designed and manufactured by the OEM • Small intricate legacy parts • Metal parts	• Parts not in stock • Parts that tie capital • Hard to manufacture • Long delivery times	• Critical old parts • Capital intensive parts	• Functionally critical parts • Small, complex parts
AM limitations	• Size of metal parts • High price of AM • Unachievable visual and surface quality	• Size and post-processing • AM inadequate for some aesthetic requirements	• Size and post-processing • Compatibility of AM materials with original materials • Speed of AM • Material joining • Quality control processes	• Cost and size • Quality • Certified materials, • IPR protection	• Material availability for certified materials • General lack of material data
Risks related to digital spare parts	• Liability of spare parts • Cyber threats • Quality control not standardized	• Quality • Brand loss in case of faulty copied parts	• Copying and printing parts by consumer • Traceability and verification • Quality	• IPR • Quality • Material quality	• Quality • Varying quality between machines • Substandard counterfeit parts
Reason for not using digital spare parts	• Lack of knowledge and experience	• High cost • Lack of knowledge and experience • Part data missing or inadequate • Difficult to identify suitable parts • Magnitude of effort to adopt	• High cost • Lack of knowledge and experience • Lack of existing ecosystem • Existing attitudes	• High cost • Lack of knowledge and experience • No belief in quality • Data management	• Part data missing or inadequate • Doubts of quality • Lack of knowledge and experience • Lack of time in companies
Identifying potential digital spare parts	• Identification according to function	• Systematic study of existing spare parts with weighted parameters	• Companies must partner with experts	• Indicators: manufacturing costs, previous manufacturing method, file size	• Hand picked
Party to propose using digital spare parts	• Design departments of OEMs	• Customer base	• Top management	• Designers, if given time and resources	• Business part of company
Special requirements of digital spare parts	• No special requirements	• Safety norms and standards should be fulfilled • Certification needed	• Recyclability	• Modification of parts not designed for AM	• 3D Model necessary
Workflow of digital spare parts	• A 3D model can be made from very little data • The function of the part is required knowledge	• Improvements based on user feedback on part • 3D model is compulsory because drawings are out of date	• Insurance needs to be informed • Manufacturer has liability for failures	• Improvements based on user feedback on part • Standardized process for delivery and file types	• The function of the part and original manufacturing method is required knowledge
Interest in smart spare parts	• Useful in special cases	• Small benefit in complexity reduction	• Very interested in embedded sensors for more data	• Smart spare parts could provide data to iterate better parts	• Interesting but impractical
Business case for digital spare parts	• Charging companies for guaranteed availability	• Creating spare parts no one else makes • Charging for higher service quality	• Charging for reduced risks of customer • Charging for certification, verification and tracing of parts	• Exploit data from smart spare parts in product design	• Charging companies for data handling, improved design, and availability

The highest level of consensus among the answers was found in the foremost reason why companies do not use AM in spare parts. The general opinion was that OEMs did not have enough experience in applying AM in spare parts and practical opportunities had not yet become known. The latest information was missing from stakeholders in all parts of the spare part supply chain because few use cases of AM in spare parts with significant practical information were publicly available. Many interviewees voiced the need for detailed in-depth case examples.

> *'Take one hundred Finnish machine workshops at random, there may be one or two experts on additive manufacturing'*
> – *AM Engineer, Group 1*

> *'There is not enough experience to support this manufacturing method. […] There are a few examples that promote this possibility, but its widespread use is missing.'*
> – *OEM Manager, Group 2*

> *'There is no information. There's of course some examples of someone using it, but those are mostly trivial or curiosities.'*
> – *Quality inspector, G3*

> *'Additive manufacturing as a manufacturing method is still too unkown. There is no belief in quality and there is a lack of courage to just try.'*
> – *OEM Engineer, G4*

> *'There should be publicly distributed information so we can get it [DSP] started. If the design process should begin by optimizing the part based on material strength – how can you design a part if you don't have the information on the material?'*
> – *OEM Engineer, G4*

> *'We need a true business case where companies get more money or save money.'*
> – *AM Manager, G5*

OEMs were generally not willing to commit to a systematic implementation of additively manufactured digital spare parts due to the resource intensive nature of changing spare part supply chains to support AM. Another challenge for OEM managers was that there were hundreds of design groups within large OEMs and they all needed AM education for the designers to know what parts could be additively manufactured.

> *'We have fifty to one hundred engineering design groups globally, so if we train them for the state of the art and future of additive manufacturing, it will take considerable resources.'*
>
> – *OEM Manager, Group 2*

AM service provider operators mentioned the uncertainty regarding liability in defective spare part as the foremost risk when employing AM. To them, it was unclear whether the responsibility for the performance of digital spare parts lay with the designer, manufacturer or with the material supplier.

> *'If a part is 3D printed that used to be made with some other method, is the onus on the designer or the printer operator? Is it the fault of the the material supplier if the part doesn't work?'*
>
> – *AM Engineer, Group 1*

A clearer view on this was provided by institutions who assert that ultimately vendors of spare parts must answer for the quality of the spare part.

> *'The vendor is responsible as they have the customer contact and the monetary interaction'*
>
> – *Quality inspector, Group 3*

Insurance companies were more concerned about spare parts created by consumers as they might lack necessary expertise to create reliable parts.

> *'[...] customers will be able to scan parts and print them on their own 3D printer. And they don't necessarily know that we have strength calculations and such, and instead they just print something that fits.'*
>
> – *Insurance company representative, Group 3*

The role of quality as a major risk was put forth by all groups. The OEM managers pointed out that AM needs new quality control processes because current ones cannot guarantee reliable results.

> *'Current quality control processes will not necessarily guarantee equally reliable results for additively manufactured parts as they do for old parts'*
>
> – *OEM Manager, G2*

AM managers saw the long-term functionality of additively manufactured spare parts and the varying quality between machines as risks.

> *'If somebody orders the same part from us three with the same nylon made, it's gonna be a completely different, looking different, tolerances different, part in mechanical properties.'*
>
> – *AM service provider manager, Group 5*

The lack of production data was often cited as the most problematic aspect of the digital spare part workflow. AM operators said that a 3D model could be made from very little data, but the functional information of the part must be available.

> *'If there's any sort of file or document, most of us can convert it into a printable object. But we need to know what the part is for."*
>
> – *AM Engineer, Group 1*

The OEM managers said that having a 3D model was nearly compulsory because drawings were usually not up to date for older parts and it is difficult to know what considerations went into designing the part without a model. OEM designers also expressed that drawings are not the best source of information because they do not show design intent.

> *'Drawings are not necessarily up to date and it is difficult to see from drawings why and how the part was designed'*
> – *OEM Manager, Group 2*

> *'Too often a drawing is slapped on the table and it is said that we cannot reach this surface roughness and there is no case even if there could be.'*
> – *OEM Designer, Group 4*

The AM managers expressed the need of 3D models, drawings, sample models, technical specifications, and production instructions of how the original part was manufactured and a description of the function of the part. Otherwise, the manufactured part had a high risk of not being fit for purpose.

> *'We just get the 3D file, we give the price, we print and then send it to our customer who finds out that it didn't exactly work.'*
> – *AM Manager, Group 5*

Designers and managers of OEMs were identified as the initiators of additively manufactured spare part adoption. The quality inspection and insurance institutions, as well as AM service provider managers said that OEM managers must initiate the use of AM in spare parts. AM service provider operators pointed to the design departments of OEMs as initiators, who expressed their willingness to suggest suitable digital spare parts if they are given the time to perform the analysis.

> *'Designers [...] should be given goggles in the morning to go through their own designs and see what [...] benefits can be found.'*
> – *OEM Designer, Group 4*

5 Discussion

The lacking level and control of quality in AM as posited by ***H1*** is backed by strong evidence. The code “quality” is the nucleus of its own co-occurrence cluster with strong connections to “problem”, “risk”, and “material”, and quality is also listed as a risk by every group and as a limitation by most groups. The strongest code co-occurrence (0.36) is between codes “risk” and “quality”, which indicates that quality is seen as the most significant risk by the interviewees. The insufficient level of quality noted by the interviewees is in line with the notion that quality is a significant technical barrier of AM in spare part implementation, as presented in Holmström et al. (2017), Chekurov and Salmi (2017), and Kretzschmar et al. (2018).

There is also evidence that the difference in performance between same type of machine is perceived as a major issue, as presented by Chekurov et al. (2018), Weller et al. (2015), and Bonnín Roca et al. (2019). A recent article suggests that quality and quality repeatability are still pervasive problems across AM materials and machine systems (Dowling et al., 2020). Both the quality of AM parts and risks in quality reliability are therefore verified as major barriers of AM implementation in spare parts, which are also the foremost barriers in the previous studies by Martinsuo and Luomaranta (2018), and Durach et al. (2017).

The issues with quality put forth by the interviewees and also reported by Holmström et al. (2017), Chekurov and Salmi (2017), and (Kretzschmar et al., 2018) relate to a lack of confidence that a spare part designed for another method could be reliably manufactured with AM to meet the same functional requirements. The engineers interviewed in our study understand that this problem can be overcome by redesigning the parts for AM, but they lack the necessary experience and knowledge regarding AM materials and design for AM. Additionally, documentation of the functional requirements of the part is often lacking, which further complicates the redesign task. The barrier of quality as described by the interviewees could therefore be mitigated by investing in acquiring the lacking knowledge and detailed design data of spare parts.

Contrary to the positions of Durach et al. (2017) and Martinsuo and Linnanmaa (2018), there is no significant evidence to confirm ***H2***, the fact that production speeds, cost-effectiveness and the maximum size of possible parts in AM are insufficient. Speed of AM is presented as a limitation only by the quality inspection and insurance group and does not appear frequently with other codes. Therefore, its impact as a barrier, as mentioned by Durach et al. (2017) and Martinsuo and Linnanmaa (2018), cannot be verified by this study. Cost is mentioned in all groups except for the AM service providers and "cost" as a code is equally linked to the codes "problem" (0.18) and "possibility" (0.18), signifying that the interviewees understand both high costs of AM and potential savings of AM. While high cost of AM machines and materials and low throughput are reported as barriers for AM implementation in general, the higher manufacturing cost is offset in the context of spare parts by the benefits brought by lower inventory costs, faster repairs, and shorter machinery downtimes. Cost is therefore a minor aspect of additively manufactured spare parts, as is also reported by Durach et al. (2017). The limited maximum size of AM is mentioned in the focus group interviews, especially related to metal parts, but it does not appear among the most frequently used codes and is therefore considered a minor barrier. This is in line with Kretszchmar et al. (2018), who report that the current volume of AM machinery is sufficient for a large portion of industrial needs of spare parts.

There is evidence to support ***H3***, regulatory structures acting as a barrier, but the evidence is not strong. The primary concern of the interviewees is that current certification and standardization processes should be revised for additively manufactured spare parts as the current processes in the domain of machine building are insufficient. However, this concern does not indicate an insurmountable barrier and the quality inspection institutions present that processes certifying additively manufactured parts can be implemented once there is enough demand. The issues of certification and standardizations are present in some focus group interviews, but not all, and the codes “certification” and “standardization” are linked to codes “quality” and “risk” at moderate strength (0.17-0.19). Regulatory structures regarding additively manufactured spare parts affect the risks of implementation, as presented by Steenhuis and Pretorius, (2017), Ballardini et al. (2018) and Verboeket and Krikke (2019), but they do not form a major barrier for the participants of this study.

There is likewise no strong evidence to verify ***H4***, insufficient security in ICT structures, as a barrier. The focus group interviews indicate that the participants are aware of the IPR issues related to digital spare parts and the issue of substandard counterfeit parts is discussed in multiple groups. In this sense, the findings support the reports of Ballardini (2018), Chekurov (2018), Rogers (2016) and Martinsuo and Linnanmaa (2018). However, “data safety” as a code does not appear in the ten most common codes of any group and it is not found in the co-occurrence network. While the participants understand the issue of cyber security in the context of spare part design data, they also provide examples of several possible solutions of protecting it, such as file encryption and advanced watermarking techniques. The reason for the contrary result of this study can be found in the elapsed time between the publication of the cited literature and the focus group interviews. The review article of Rogers (2016) was written and the empirical parts of Ballardini et al. (2018) and Martinsuo and Linnanmaa (2018) were conducted several years before the focus group interviews of our study. In the meantime, several commercial solutions to cyber security in additive manufacturing were released by established actors and start-ups, which may have influenced the attitudes of the interviewees.

The lack of expertise in all areas of the supply chain as a barrier, ***H5***, is supported by strong evidence, which corroborates the findings of Dwivedi et al. (2017), Thiesse and Buckel, (2015) and Heinen and Hoberg (2019). The strong co-occurrence of the codes "additive manufacturing expertise" and "problem" (0.22) is indicative of the issue. The participants of the focus group interviews are generally aware of the theoretical possibilities of using AM in spare part production and they can readily name examples of cases where it has been used. Nevertheless, the participants clearly indicated that there is a severe lack of examples that explain the detailed workflow and the ecosystem of digital spare parts. The specific points that the interviewees require from the case examples are material quality and design considerations. This is in line with the findings of Yi et al. (2019) who report that lack of material data and design knowledge are holding back AM implementation. Regarding the finding by Murmura & Bravi (2018) that lack of knowledge is not an issue among companies that have already started using AM, the result cannot be corroborated because the interviewed companies that already do use AM still maintain that they lack required knowledge.

The resistance to change as a barrier, ***H6***, is only mentioned a handful of times on the level of individuals and, in those cases, it is attributed to the lack of time of employees to adopt new technologies. The resistance to change on an organizational level is more prominent as companies do not want to commit due to the magnitude of the change. However, the codes related to this topic are not found among the most common codes and do not appear in the co-occurrence network. The finding that resistance to change is a major barrier, as presented by Dwivedi et al. (2017) and Martinsuo and Luomaranta (2018), can therefore not be fully corroborated by this study. The difference in findings can be attributed to the fact that Dwivedi et al. (2017) refer to resistance to change in floor workers of factories. The interviewees of our study were managerial workers except for

AM service provider machine operators, who are already familiar with AM technology do not therefore resist it. While it is possible that the machine operators of the OEMs do present change resistance towards AM, they are not involved in the decision-making process of implementing digital spare parts.

Aside from the hypotheses, another clear barrier was discovered through qualitative and quantitative analysis. The importance of design data in the success of implementing AM in spare parts, and the fact that the data is lacking is recognized by all groups and the code "data for digital spare parts" strongly co-occurs with "requirement" (0.22). Participants dealing directly with the design and production of parts emphasize that the function of spare parts is the most important information and all groups put functionality forward as the minimum requirement to evaluate if the spare part can be manufactured with AM, while at the same time being data that are rarely available in technical drawings or 3D models. Although this finding is prominently featured in the focus group interview results, the code "data for digital spare parts" is strongly linked only to the code "requirements" in the code co-occurrence network, and not to the code "problem". This implies that while the participants realize the importance of data, they are also confident that it can eventually be acquired. Nevertheless, companies do not yet know how to integrate functionality information in their 3D models systematically. Although the availability of data being a barrier was not one of the hypotheses, it has been previously noted by Martinsuo and Luomaranta (2018) who report that subcontractor machine operators and designers struggle with missing or insufficient part design data. Our findings indicate that the appreciation of the necessary quality and availability of data has spread to the managerial level of AM service providers and OEMs. Martinsuo and Luomaranta (2018) posit that advanced 3D model file types with supplementary data for manufacturing could be used to overcome the barrier. This is in line with our finding that companies are passively waiting for a file format that could encapsulate the functionality of the part.

We have found that not all barriers that are presented in literature pose an insurmountable barrier for additively manufactured digital spare part implementation. There was no strong evidence to support hypotheses ***H2***, ***H3***, ***H4***, and ***H6*** and they are therefore rejected in this study. This study confirms that ***H1***, quality issues, and ***H5***, lack of expertise, and the lack of high-quality design data are the key barriers responsible for lagging adoption of digital spare parts in the machine-building industry. Furthermore, we have found that the three key barriers are interconnected. The lack of trust in quality of AM is driven by the lack of knowledge and documentation of spare part functionality. Therefore, providing design engineers with detailed material knowledge and investing in systematic accumulation of functional design data of spare parts are the most relevant actions to achieve a more widespread adoption of digital spare parts in the machine-building industry and other industries where additively manufactured digital spare parts are rarely used.

6 Conclusions

In this study, focus group interviews were conducted with five groups of relevance to the implementation of AM in spare part supply chains: designers and managers from OEMs, operators and managers from AM service providers, and representatives of insurance and quality inspection institutions. The primary interest of the study was to identify the key barriers causing the delay of deployment of digital spare parts in the machine-building industry. The focus group interviews were recorded, transcribed, and analyzed with qualitative and quantitative methods.

The article set out to verify six hypotheses for barriers that are delaying the implementation of digital spare parts. There was strong evidence to verify H1 (quality issues) and H5 (lack of knowledge), moderate evidence to verify H3 (regulatory issues) and H4 (IPR issues), and little evidence to verify H2 (speed, maximum size, and cost issues) and H6 (resistance to change). In the parsing of the data, the importance of data availability was identified as a major barrier although it was not an initial hypothesis.

Of the three key barriers, one is technical and two are operational. However, we have found that the technical barrier of quality can be mitigated by investing in AM material and design knowledge and by systematically gathering functionality data on spare parts. We encourage researchers, educators, and corporate managers to promote actions that would reinforce the AM knowledge of the current and future workforce, as this will likely lead to a greater adoption of the digital spare part concept.

6.1 Theoretical implications

The article contributes in several ways to the discussion surrounding AM barriers in spare parts. This is the first article to present a broad study on additively manufactured spare part adoption in the machine-building industry, as well as the first study to explore the barriers of AM adoption in spare parts with a cross-organizational focus group interview approach. The findings of the article can guide researchers to map the research needs in their respective fields, further identify the most important barriers of AM integration in spare parts, and work towards goals with the highest impact.

The article contributes to the theory of digital spare parts by providing the hitherto lacking explanations for the delayed implementation of digital spare parts in industries outside the automotive and aeronautical sectors. The key barriers are reported, and their connection is interpreted. The barriers that are present in literature but are not corroborated by the study are rejected and the cause for not finding evidence to support them is theorized upon.

6.2 Practical implications

The findings of the article provide insights for managers on how to achieve higher levels of additive manufacturing integration in spare part delivery operations in the context of the machine-building industry and other industries that are lagging in digital spare part implementation. Based on our results, companies can carry out actions with high impact, which are acquiring AM-specific material and design knowledge and creating a strategy for building a database of 3D models that carry all necessary information for modifying the parts for AM. The results can also help consultancy companies advising OEMs in AM adoption in spare parts. While the needs of every company and industrial cluster should be mapped individually, the findings of the study offer a solid starting point.

Based on the qualitative findings, designers in OEMs are the actors most likely to be on the frontline of AM adoption in spare parts. Resources should be allocated to the designers by companies so that they can gain experience in the practical issues of AM, as well as training in design and supply chain aspects of AM. On the other hand, managers should also receive practical training in AM. Our findings indicate that corporate managers understand the broad benefits of additively manufactured spare parts, but they cannot proceed with confidence in their adoption because they do not have enough practical expertise.

Deploying AM in spare parts delivery operations requires large modifications to existing supply chains, to which companies are not willing to commit without clear knowledge on how they will benefit and what issues to expect. To overcome the major barrier of lacking AM expertise, we recommend that the results of publicly funded efforts aimed at accelerating AM adoption in spare parts, such as educational AM workshops and consultancy events, should lead to publicly available and highly detailed case studies that demonstrate how digital spare parts can be taken from an idea into actual deployment and what specific expertise is required.

6.3 Limitations of the study and future work

Aside from two exceptions in the group of AM service provider managers, the participants of this study are from Finland and the companies they represent are headquartered in Finland. This naturally causes a bias towards the attitudes and experiences found in Finnish manufacturing industry, in which machine-building is prominent. In 2017, the manufacture of machinery and equipment accounted for 13.5% added value of the entire Finnish manufacturing industry. When comparing Finland to other EU countries in terms of share of production value of machine-building in the manufacturing industry, Finland is third (13.5%) after Denmark (19.2%) and Germany (13.6%) (Eurostat, 2020).

While the intent of the study was to explore the barriers of implementation in the machine-building industry, the results could be transferred to other sectors with additional focus group interviews. The next steps of the research on the adoption of additive manufacturing in spare part production will include a series of in-depth expert interviews conducted with representatives of OEMs, AM service providers, and quality inspection and insurance institutions in countries with industry structures dissimilar to those of Finland.

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